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MAY 1963

HIGH ENERGY RATE FORGING DEVELOPMENT

J. M. Palsulich

Western Gear Corporation

Systems Management Division

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Precision Forge Co.

(Forging Subcontractor)

Contract: AF 33 (600)-42523

AMC Project: TR 7-866

Fifth Interim Technical Progress Report

10 October 1962 - 10 May 1963

AMC Aeronautical Systems Center

Air Material Command

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ASD Project Engineer: L. C. Polley

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ABSTRACT - SUMMARY

Successful high energy rate forging of unwrought refractory materials is highly dependent upon the forging configuration and die design. Good forgings are possible when working stresses are compressive in nature. Tensile and shear stresses during forging generally result in fracturing of the billet if the refractory metals have received little or no plastic work.

Data for forging conditions and results of metallurgical examinations are presented.

FOREWORD

This Interim Technical Progress Report covers a portion of the work on Phase III performed under Contract AF 33(600)-42523 from October 1962 to May 1963. It is published for technical information only, and does not necessarily represent the recommendations, conclusions or approval of the Air Force.

This program is being conducted by the Systems Management Division of Western Gear Corporation, Lynwood, California. It is under the direction of Mr. L. C. Polley of the ASD Basic Industry Branch, Wright-Patterson Air Force Base, Ohio. Mr. J. M. Palsulich, Research Metallurgist is project engineer and technical supervisor. Mr. M. L. Headman, Manager of Research is program manager.

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INTRODUCTION

The refractory metals are a group of materials which generally include those metals whose melting points are equal to, or higher than, 3400°F. There are many refractory metals with widely varying properties and availability. At the present time, these metals are the subject of intensive investigation because their high temperature strengths and high melting points are required in space vehicles, advanced aircraft, and nuclear energy applications. For various economic and technological reasons the refractory metals currently of most importance are tungsten, tantalum, molybdenum, niobium and chromium.

The production, fabrication and machining of the refractory metals present major problems which result in elevated costs. Using presently accepted forging and manufacturing techniques, as much as 350 pounds of material are required to make a 35 pound part. Therefore, any improvement in forging technique that can provide better material utilization will result in greater efficiency of the forging process and provide substantial cost savings. These cost savings are possible through reduction of initial material costs and substantial reduction in the cost of machining to finished dimension.

This investigation of high energy rate forged refractory materials was prompted by the demonstrated ability of the high velocity forging process to produce close tolerance precision forgings while providing better material utilization. Effective utilization of the process is also enhanced by the fact that forging temperature for a given material can be reduced to within the furnace capabilities of most companies in the metalworking field.

All forging in this program is being performed on a 1220 B Dynapak high energy rate forging machine manufactured by the Advanced Products Department of General Dynamics Corporation. This report discusses the experimental results obtained during the reporting period from 10 October 1962 to 10 May 1963.

Program Objective

The objective of this program is to determine the suitability of the high energy rate forging process using a Dynapak machine for the production of aerospace hardware. The investigation includes a variety of materials of current interest. Emphasis is placed on evaluating the metallurgical structure and the mechanical properties of the materials when forging parameters are varied. Information on die design, forging temperature, mechanical properties, hardness, microstructures and other pertinent material and manufacturing data will be developed.

Phase I - State-of-the Art Analysis

During this phase, a state-of-the art survey was conducted to determine current activity in high velocity pneumatic forging. During this phase, a satisfactory procedure for subsequent phases was established.

Phase II - Forging of Low and Medium Temperature Alloys

Under this phase, high velocity forging of the following materials was studied: 6 Al-4V alpha-beta titanium alloy; AISI 4340 medium alloy steel; type H-11 tool steel; and PH 15-7 Mo precipitation hardening stainless steel. Phase II was divided into two sections: upset forging billets to approximately 80% reduction, and the forging of specific geometries.

Phase III - Forging of Two Refractory Metals

This phase is to investigate the possibility of forging commercially pure tungsten and TZM molybdenum alloy to close tolerances and to determine the various forging parameters necessary to insure high quality forgings. After forging parameters have been established, subsequent forging of specific geometries will be accomplished.

DISCUSSION OF PHASE III

Materials and Procedure

Two materials are currently being investigated under Phase III of the program, i.e., commercially pure tungsten and the TZM molybdenum alloy. Pressed-and-sintered and arc melted-and-centrifugally cast billets of both tungsten and TZM molybdenum alloy are used as starting material. All billets have the nominal dimensions of two inches in diameter by two inches long. The arc melted billets were ultrasonically inspected and all were sound. Both the pressed and sintered and arc melted billets were found to be free from any surface cracks when examined by the dye penetrant inspection method. Chemical analysis of the billets as supplied by the vendors is shown in Table I.

During this reporting period work continued on developing forging techniques to forge these materials into a rocket nozzle insert as shown in Figure 12. All billets were heated to forging temperature in a Lindberg recirculating gas-fired furnace. Heating was accomplished without the use of a protective atmosphere since it was previously established that metal losses due to oxidation were relatively low (under 3%).

Subsequent to forging, all parts were placed in lime to prevent rapid cooling and cracking. Stress relieving and recrystallization was performed under an argon atmosphere in a Pereco glo-bar furnace.

The rocket nozzle inserts were forged in two stages. Blocking was performed using a flat punch and the finisher bottom die. Finishing was performed with the bottom die used in the blocking operation and a punch that conformed to the I.D. dimensions of the finished part.

It should be noted that both the TZM molybdenum arc melted and centrifugally cast billets and the TZM alloy pressed and sintered billets used in this program had never been produced before and were considered experimental by the suppliers.

Results

I. Billet Material Examination

Many problems occurred during the development forging of the rocket nozzle configuration. Generally speaking, the blocking operation presented very few difficulties. However, in most cases, severe cracking occurred during finish forging of the blocked parts. The following procedures were observed:

TABLE I

ANALYSIS OF TUNGSTEN AND TZM MOLYBDENUM BILLETS

Element	Pressed and Sintered Billets		Arc Melted Billets	
	Tungsten (ppm)	TZM Molybdenum (ppm)	Tungsten (ppm)	TZM Molybdenum (ppm)
C	*30	40	40	230
O_2	*50	2300	*20	50
Ti		4400		5000
Zr		1250		650
N_2	*30	25		
H_2	1.5	4.4		
Al	*20	*20		
Co	*20	*20		
Cr	*20	*20		
Cu	*40	*40		
Fe	*100	*100		
Mg	*20	*20		
Mn	*20	*20		
Ni	*25	60		
Pb	*20	*20		
Si	*100	100		
Sn	*50	60		
V		25		
Mo		Remainder	2800	Remainder
W	Remainder		Remainder	650

* Less than

A. Macro-Examination

Macro-examination of the arc melted tungsten and TZM billets disclosed a columnar grain structure at one end of the billet and the equi-axed grains at the other end (Figure 1). Most of the billets had been forged before this fact was discovered. Upon checking with the supplier, it was learned that seven tungsten and seven TZM molybdenum alloy billets could have been in this condition. All of the TZM alloy billets with the columnar structure and all but one of the tungsten billets were forged.

Grain size of the as-received pressed and sintered billets ranged between 4 and 6 on the ASTM ferrous grain size charts (Figures 10 and 11). The arc melted tungsten grains were between 1/16 inch and 1/32 inch in diameter and some of the columnar grains were 3/4 inch long. Grains in the arc melted TZM molybdenum billets were slightly smaller than those in the arc melted tungsten billets.

B. Micro-examination

An extensive micro-examination of the forged pressed and sintered TZM alloy parts showed a large number of inclusions and many areas of porosity (Figures 2-9). Hardness of the inclusions was determined on a Wilson microhardness tester utilizing a 100 gram weight. The average Knoop hardness of the particles was 900. This roughly corresponds to a Rockwell C hardness of 67. It is thought that these particles may be a titanium carbide. However, no analysis was performed to verify this.

II. Closed Die Forging

A. TZM Molybdenum

In the previous reporting period, the program had met with a large degree of success. Sound forgings having a wall thickness of approximately 0.090 inch were produced from both arc melted and pressed and sintered billets (Figures 12, 13 and 14). These forgings were produced in the following manner.

Blocking was performed in one blow using a fire pressure of 900 psi, 6-3/8 inch stroke, and 2200°F forging temperature. The blocked forgings (Figure 15) were then cooled in lime to room temperature. Next, the forgings were heated to 2050°F and struck two to three blows in the finisher dies with a fire pressure of 400 psi. Reheating was performed between each blow. This procedure resulted in sound forgings approximately 80% of the time (Figures 12, 13 and 14).

During the present reporting period, a new approach was taken. It was decided to lower the forging temperature during the blocking operation to 2100°F and use two to three blows of low energy to block the parts.

Group I. Three arc-cast billets were struck three blows in the blocker die with a fire pressure of 450 psi and a forging temperature of 2100°F.* There was no evidence of cracking after the first, second or third blows. The same procedure was repeated for three pressed and sintered billets. One of the pressed and sintered billets cracked on the third blow. The part that cracked bounced out of the die as it was being struck.

The finisher die was placed in the machine and one of the pressed and sintered billets was struck at 1950°F with a fire pressure of 500 psi. It exhibited severe radial cracking through the flash zone and into the body to the forging. Next, the forging temperature was increased to 2050°F keeping the fire pressure at 500 psi. This forging cracked in the same manner as the previous one. Maintaining the 2050°F forging temperature, the next three forgings were struck blows at 400 psi. One of the three cracked radially through the flash (Figures 16, 17 and 18).

Two forgings out of the original six were sound at this time. Using a forging temperature of 2050°F and a fire pressure of 400 psi, both parts were struck. The wall thickness at this time was approximately 0.120 inch. It was decided to give each part one final blow at 500 psi fire pressure in order to reduce the wall thickness to 0.100 inch. Both forgings severely cracked during this operation.

Group II. Two arc cast and two pressed and sintered TZM molybdenum alloy billets were struck three blows in the blocker die using a fire pressure of 600 psi and a forging temperature of 2100°F. All blocked forgings were sound. The forgings were then stress relieved at 2500°F for one hour. All of the stress relieved forgings were struck in the finishing dies utilizing a forging temperature of 2100°F and a fire pressure of 500 psi. Two of the forgings cracked. One of the remaining two was restruck under the above conditions. This forging also cracked. The other forging was struck onanother day using an incorrect bottom die. This incorrect die was identical to the one being utilized on this program except that the diameter was approximately 3/4 inch smaller. Five tungsten and three TZM molybdenum alloy billets were blocked in this small die. The results of using this small die are discussed elsewhere in this report.

Group III. Two arc melted and one pressed and sintered were blocked using two blows at 750 psi fire pressure at 2100°F. The forgings were subsequently stress relieved for one hour at 2500°F under an argon

* Reheating is performed between blows in all cases.

TABLE II

FORGING CONDITIONS FOR TZM MOLYBDENUM ALLOY ROCKET NOZZLE INSERT

Billet Designation	Blocking Operation						Finishing Operation						Remarks
	First Blow		Second Blow		Third Blow		First Blow		Second Blow		Third Blow		
	FP psi	Temp °F	FP psi	Temp °F	FP psi	Temp °F	FP psi	Temp °F	FP psi	Temp °F	FP psi	Temp °F	
TZMC-1	1100	2200					700	2200					Flash cracked in blocking.
-2	1100	2200					700	2200					Cracked areas removed
-3	1100	2200					700	2150					and forgings struck in
TZMP-1	1000	2200					700	2200					finisher. Incomplete
-2	1000	2200					700	2150					fill in some areas.
-3	1000	2200					700	2150					
-4	900	2200					400	2050	400	2050			Some parts edge cracked
-5	900	2200					400	2050	400	2050			in final blow - two
-6	900	2200					400	2050	400	2050			excellent forgings.
-7	900	2200					400	2050	400	2050			
-8	900	2200					400	2050	400	2050			
TZMC-4	900	2200					400	2050	400	2000			Part cracked final blow
-5	900	2200					400	2050	400	2100			Sound Part
-6	900	2200					400	2050	400	2200			Sound Part
-7	450	2100	450	2100	450	2100	500	1950					Cracked severely
-8	450	2100	450	2100	450	2100	500	2050					Cracked severely
-9	450	2100	450	2100	450	2100	400	2050	400	2050	500	2050	Flash cracked into part
TZMP-9	450	2100	450	2100	450	2100							Cracked in blocking
-10	450	2100	450	2100	450	2100	400	2050	400	2050	400	2150	Flash cracked into part
-11	450	2100	450	2100	450	2100	400	2050					Cracked at flash line
-12	600	2100	600	2100	600	2100	400	2150				With blocking die	Severely cracked
-13	600	2100	600	2100	600	2100	500	2100	Stress relieved one hour at 2500°F after blocking				Severely cracked
TZMC-10	600	2100	600	2100	600	2100	400	2150					Severely cracked
-11	600	2100	600	2100	600	2100							Cracked in blocking
-12	750	2100	750	2100			500	2100				With blocking die	Severely cracked
-13	750	2100	750	2100	Stress relieved one hour at 2500°F.		500	2100	500	2100		With blocking die	Severely cracked
TZMP-14	750	2100	750	2100			500	2100	500	2100		With blocking die	Severely cracked

atmosphere. Next, the blocked forgings were struck with the finisher dies. The pressed and sintered part cracked and the arc melted ones held together. When the arc melted parts were restruck they fractured on one side. The fire pressure for both blows was 500 psi and the forging temperature was 2100°F.

All three billets were struck in blocking and finishing using the incorrect small diameter bottom die. It would be expected that the billets would rupture with the small die especially when the finisher punch was used.

The billet material was subject to extremely high shear loading at the entrance to the die due to the action of the punch and the undersize die.

Most of the other failures that were noted previously were located in the flash area and at the top of the forging. All of the failures occurring in conjunction with the undersize die went well into the body of the forgings.

B. Commercially Pure Tungsten

For the most part, the tungsten closed die forging was unsuccessful. Blocking could be successfully carried out without any external signs of rupturing. All blocking of tungsten billets during this reporting period was carried out at 2600°F using a fire pressure of 1000 psi and a stroke of 8-1/2 inches.

Some of the blocked forgings were sectioned and macroetched. Both intracrystalline and intercrystalline cracks were evident (Figure 19). This was found to be true in both the pressed and sintered and arc melted materials.

Recrystallization of the blocked forgings made little difference in the forging characteristics of the materials. As long as the billets are subjected to compressive stress, little or no surface rupturing is observed. Once the parts are subjected to tensile or shear stresses, however, severe rupturing occurs in almost every instance.

It is believed that the use of wrought billet stock made little difference in this forging program. The presence of columnar grains (Figure 20) in some of the arc melted billets were also detrimental to the forging characteristics. In the majority of cases, the tungsten forgings had many cracks whereas the TZM forgings had only one or two cracks of limited length.

III. Micro-Examination of Forgings.

Samples for micro-examination were taken from most of the forgings. All specimens were removed using an abrasive cut-off saw with copious

TABLE III

FORGING CONDITIONS FOR TUNGSTEN ROCKET NOZZLE INSERTS

Billet Designation	Blocking Operation: First Blow FP psi	Blocking Operation: First Blow Temp °F	Blocking Operation: Second Blow FP psi	Blocking Operation: Second Blow Temp °F	Blocking Operation: Third Blow FP psi	Blocking Operation: Third Blow Temp °F	Finishing Operation: First Blow FP psi	Finishing Operation: First Blow Temp °F	Finishing Operation: Second Blow FP psi	Finishing Operation: Second Blow Temp °F	Finishing Operation: Third Blow FP psi	Finishing Operation: Third Blow Temp °F	Remarks
WP-14	[illegible]00	2500											Bottom end and top cracked
WP-15	1000	2500											Bottom end and top cracked
WP-16	1200	2600											Bottom end and top cracked
WP-17	1200	2600											Bottom end and top cracked
WC-1	1200	2600					800	2400					Bottom stuck in die—die reworked
WC-2	1200	2600					800	2400					Completely fractured
WC-3	1200	2600					800	2400					Small crack in flash area
WC-4	1000	2600					800	2400					Bottom broke off
WC-5	1000	2600					800	2400					Completely fractured
WP-18	1000	2600	Recrystallized at 2500°F for one hour				1000	2600					Completely fractured
WP-19	1000	2600	Recrystallized at 2300°F for one hour				800	2500					Severe fracturing
WC-5	1000	2600	Recrystallized at 2300°F for one hour										Part sectioned
WC-6	1000	2600	Recrystallized at 2300°F for one hour				800	2500					Severe fracturing
WC-14	1000	2600	Recrystallized at 2300°F for one hour				800	2500					Severe fracturing
WC-8	1000	2600	Recrystallized at 2300°F for one hour				800	2500					Severe fracturing
WC-16	1000	2600	With Blocking Die										Only slight edge cracking
WC-18	1000	2600	With Blocking Die										Only slight edge cracking
WC-19	1000	2600	With Blocking Die										Only slight edge cracking
WC-20	1000	2600	With Blocking Die										Only slight edge cracking
WC-[illegible]	1000	2600	With Blocking Die										Only slight edge cracking

amounts of water for cooling. Both the tungsten and the TZM molybdenum alloy samples were etched subsequent to final polishing with a modified Murakami's Reagent (25% glycerol - 75% Murakami's Reagent).

Figures 21 and 22 illustrate the intragranular type cracking noted in many of the failures. The material is forged arc melted TZM molybdenum alloy. It should be noted that the grain boundaries were very fine and did not present any obstacle to cracking. The banding that is visible was not observed in all forgings, nor was it in any of the as-received billets that were sectioned. Figure 23 is a view of the banded areas at 1000X. In any given crystal, there are banded areas as well as non-banded areas.

Specimens were removed from one of the Group I arc melted TZM forgings. The specimens were forged at 2100°F and heat treated at 2300°F and 2350°F in some recrystallization primarily around the grain boundaries for three hours resulted in some recrystallization primarily around the grain boundaries and a small amount in the center of the crystals.

The pressed and sintered TZM billet forged in Group III was given a 2500°F heat treatment after forging. Only a small amount of recrystallization was observed and this was principally in the grain boundaries (Figure 27). All the forgings made from pressed and sintered billets showed very little, if any, evidence of recrystallization.

CONCLUSIONS

High energy rate closed die forging of unwrought refractory metals appears feasible providing the working stress in the part is compressive in nature. When the forging configuration is such that the principal stresses are tensile and/or shear, the forging of unwrought refractory metals is not practical. This conclusion is in conflict with the one contained in Interim Report IV in which it was stated that it would be practical to manufacture rocket nozzle inserts using unwrought arc cast materials.

It is believed that the compressive working of unwrought billets prior to forging would eliminate the problem of cracking due to tensile or shear working stress. This alternative could be evaluated with the die configuration utilized in this program.

The columnar grain structure found in some unwrought arc cast materials is very detrimental in the forging process. The use of extruded or rolled billets would obviate this condition. It is believed that high inclusion content and porosity in the pressed and sintered TZM molybdenum contribute to rupturing of the forgings. The use of arc cast and extruded billets should help to eliminate this problem.

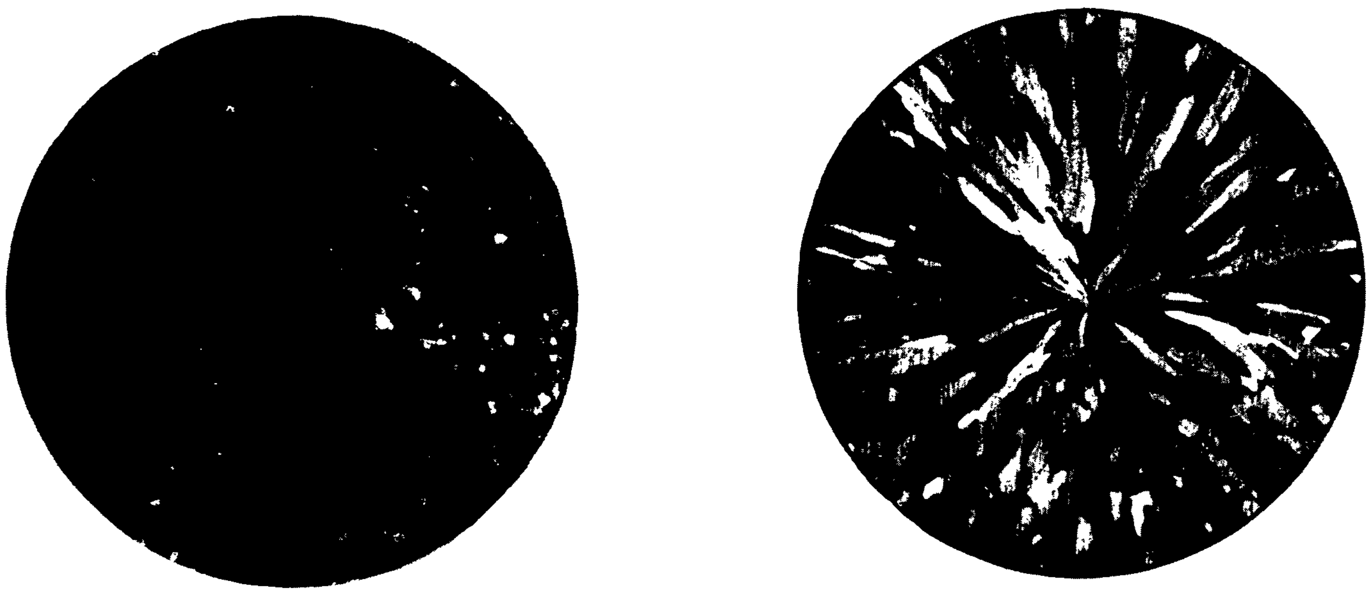


Figure 1 - Macroetch arc-melted tungsten billet showing equi-axed structure at one end and columnar grains on the other end. Approx. 1.5X mag.

Figure 2 - Photomicrograph of forged pressed and sintered TZM molybdenum alloy. Note inclusions. 100X mag. Etched with modified Murakami's Reagent

Figure 3 - Photomicrograph of forged pressed and sintered TZM molybdenum alloy. Note inclusions. 100X mag. Etched with modified Murakami's Reagent

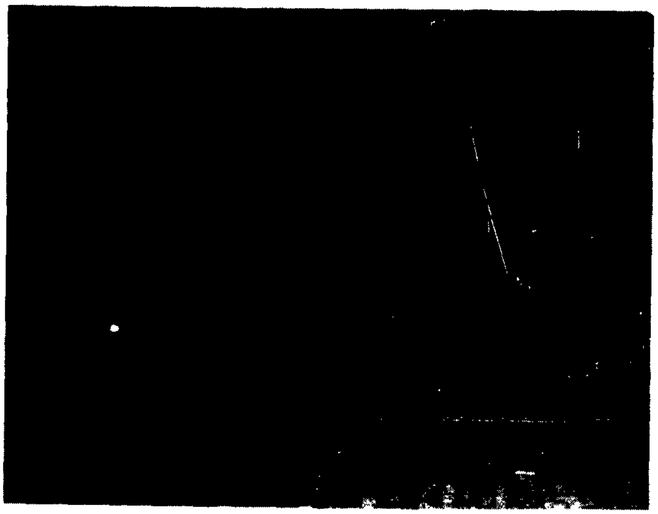


Figure 4 - Photomicrograph of forged, pressed and sintered TZM molybdenum alloy illustrating area of concentrated porosity. 100X mag. Etched with modified Murakami's Reagent.

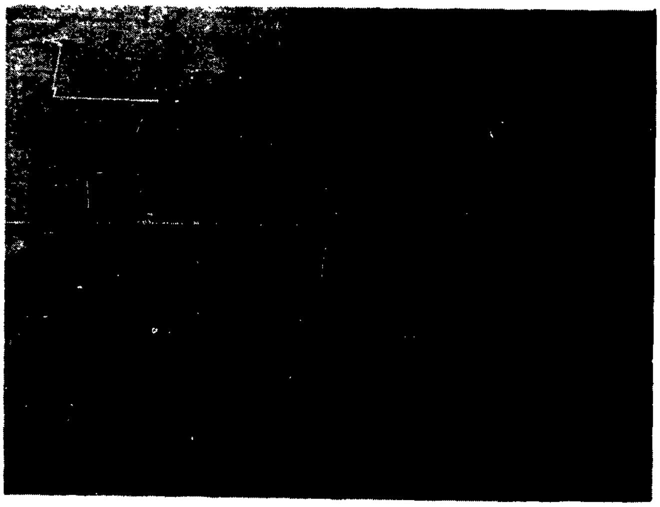


Figure 5 - Photomicrograph of forged pressed and sintered TZM molybdenum alloy. Note inclusions. 100X mag. Etched with modified Murakami's Reagent.

Figure 6 - Photomicrograph of forged pressed and sintered TZM molybdenum alloy. Note inclusions. 100 X mag. Etched with modified Murakami's Reagent.

Figure 7 - Photomicrograph of forged pressed and sintered TZM molybdenum alloy. Note inclusions. 100 X mag. Etched with modified Murakami's Reagent.

Figure 8 - Photomicrograph of forged, pressed and sintered TZM molybdenum alloy illustrating area of concentrated porosity. 100 X mag. Etched with modified Murakami's Reagent.

Figure 9 - Photomicrograph of forged pressed and sintered TZM molybdenum alloy. Note inclusions. 100 X mag. Etched with modified Murakami's Reagent.

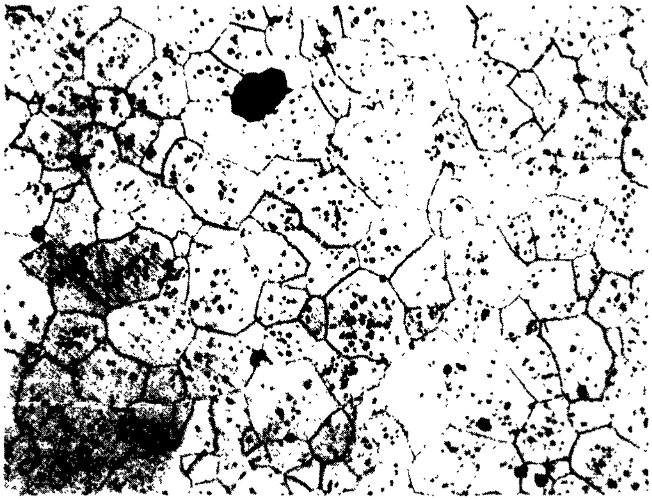


Figure 10 - Photomicrograph of as-received TZM pressed and sintered billet. 100 X mag. Etched with modified Murakami's Reagent.

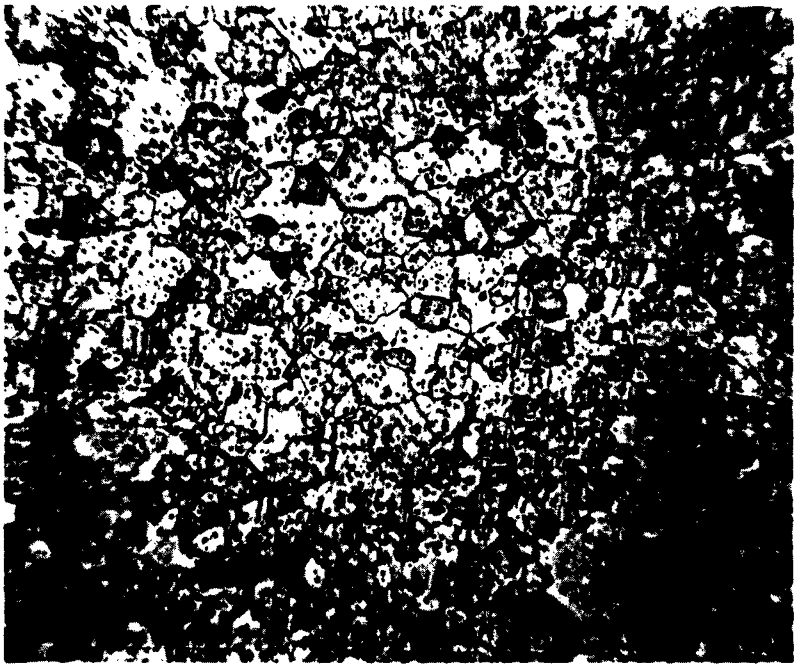
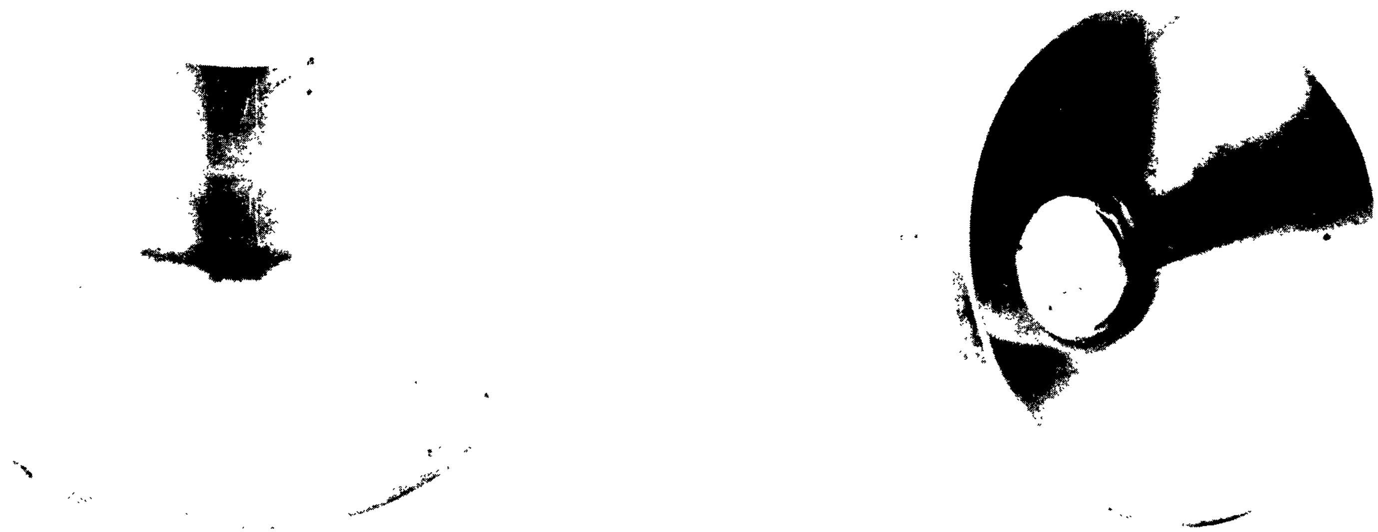


Figure 11 - Photomicrograph of as-received tungsten pressed and sintered billet. 100 X mag. Etched with modified Murakami's Reagent.



HIGH - ENERGY - RATE - FORGED

TZM MOLYBDENUM

ROCKET NOZZLE INSERT

Figure 12

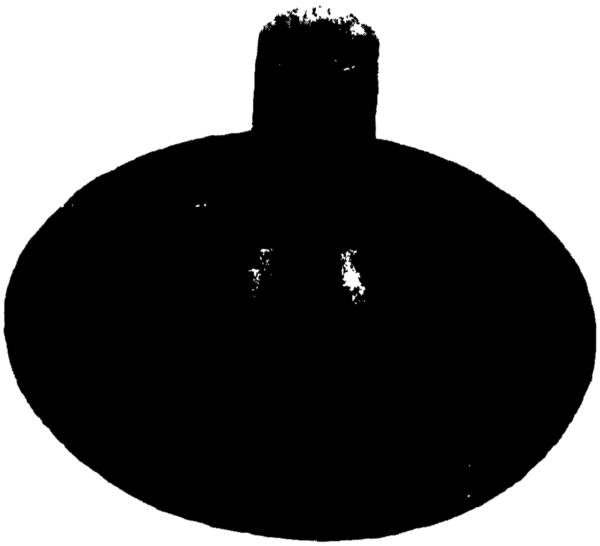


Figure 13 - Arc melted TZM billet forged into rocket nozzle insert shown in the as-forged condition.

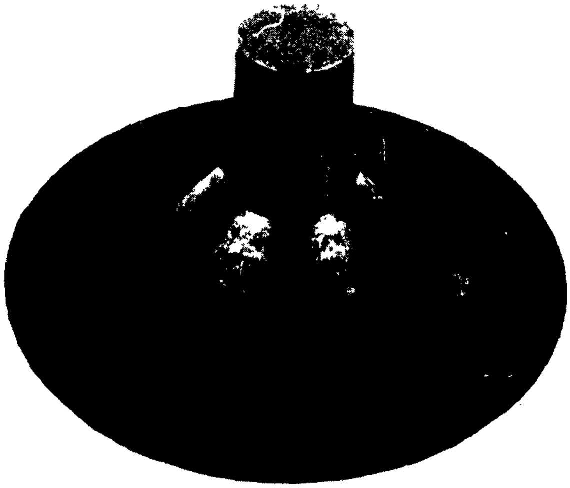


Figure 14 - Pressed and sintered TZM billet forged into rocket nozzle insert shown in the as-forged condition.

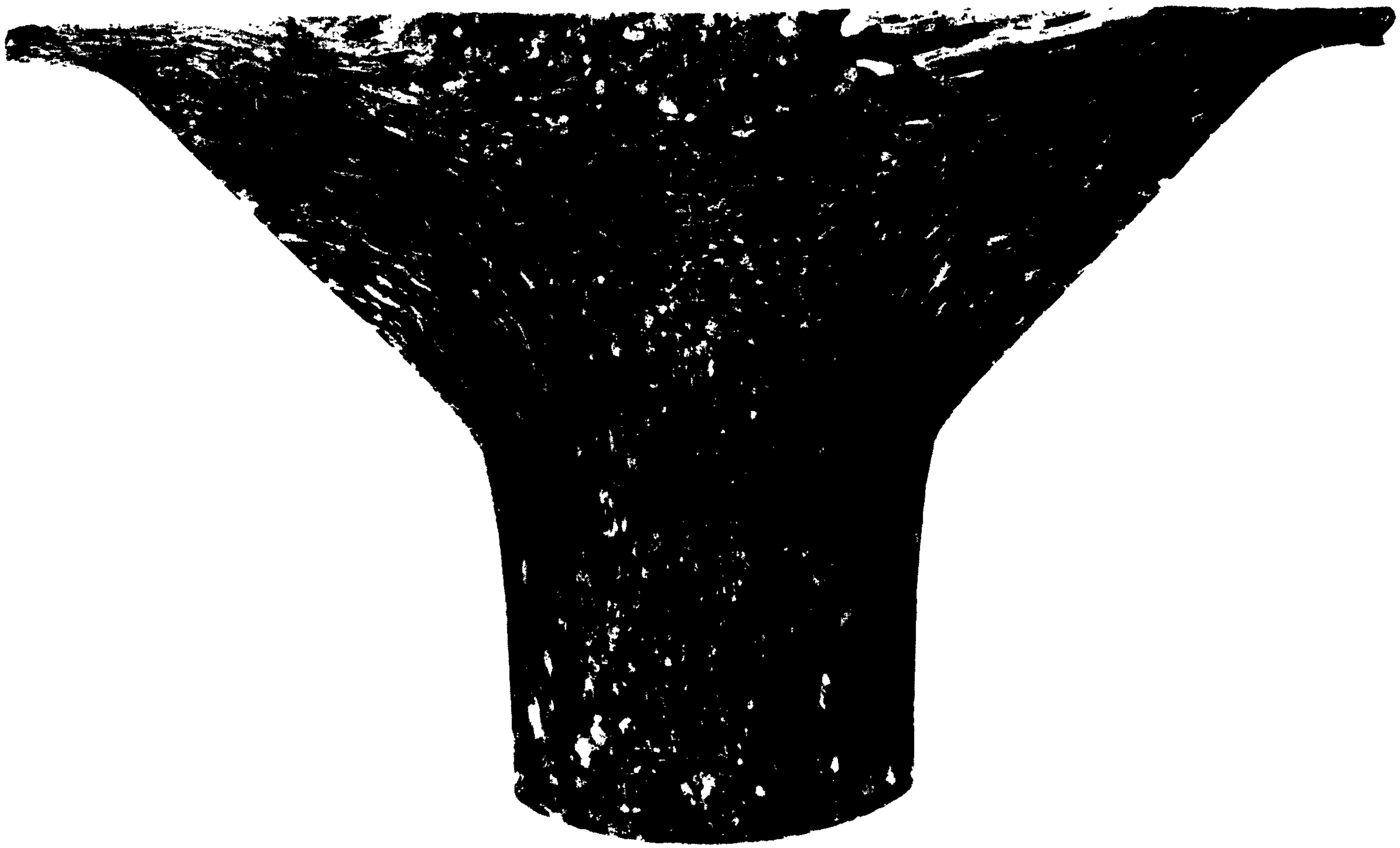


Figure 15 - Macroetched section of arc melted TZM billet in blocked condition. Crack occurred upon sectioning.

Figure 16 - Typical example of the type of failure experienced during the current reporting period. Material is arc melted TZM molybdenum alloy. Cracking was along grain boundaries.

Figure 17 - Typical example of the type of failure experienced during the current reporting period. Material is arc melted TZM molybdenum alloy. Cracking was along grain boundaries.

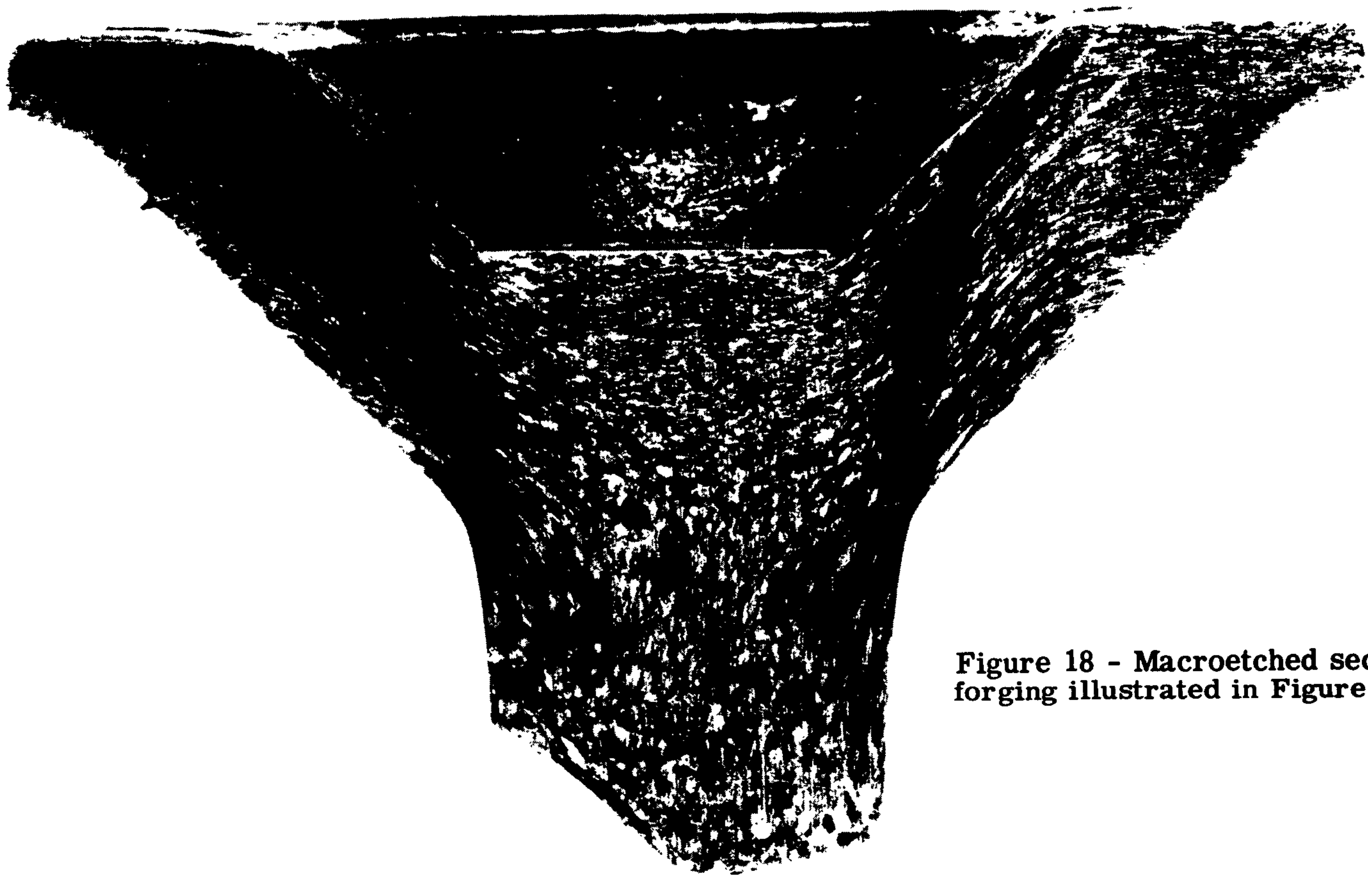


Figure 18 - Macroetched section of the forging illustrated in Figures 16 and 17.

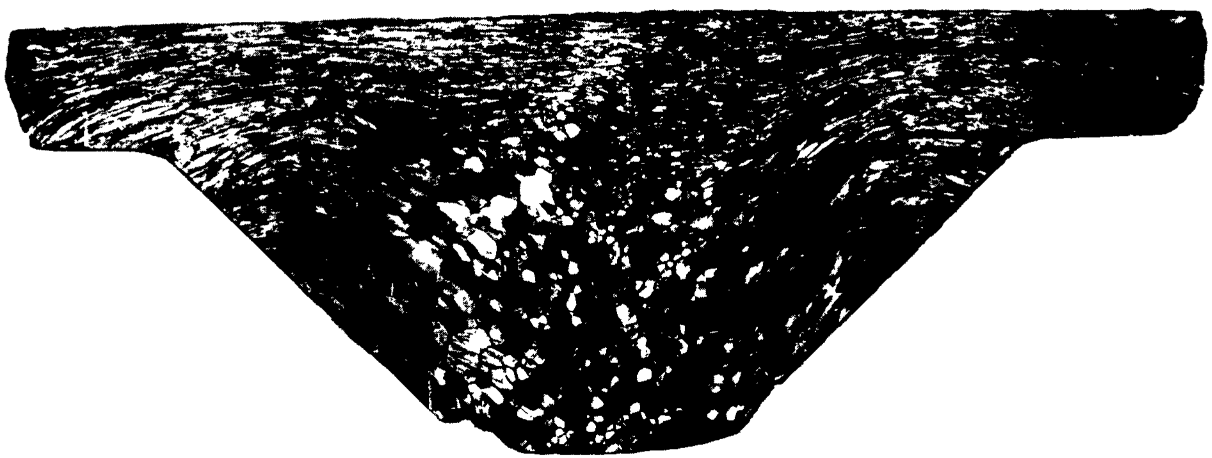


Figure 19 - Macroetched section of blocked tungsten forging made from arc melted billet. Note crack on left side of forging. Cracks are both intra- and trans-granular in nature.

Figure 20 - Top view of forging seen in Figure 19. This forging was made from billet having columnar grain structure.

Figure 21 - Example of intragranular type cracking. Material is arc melted TZM molybdenum alloy. 100X mag. Etched with modified Murakami's Reagent.

Figure 22 - Example of intragranular type cracking. Material is arc melted TZM molybdenum alloy. 100X mag. Etched with modified Murakami's Reagent.

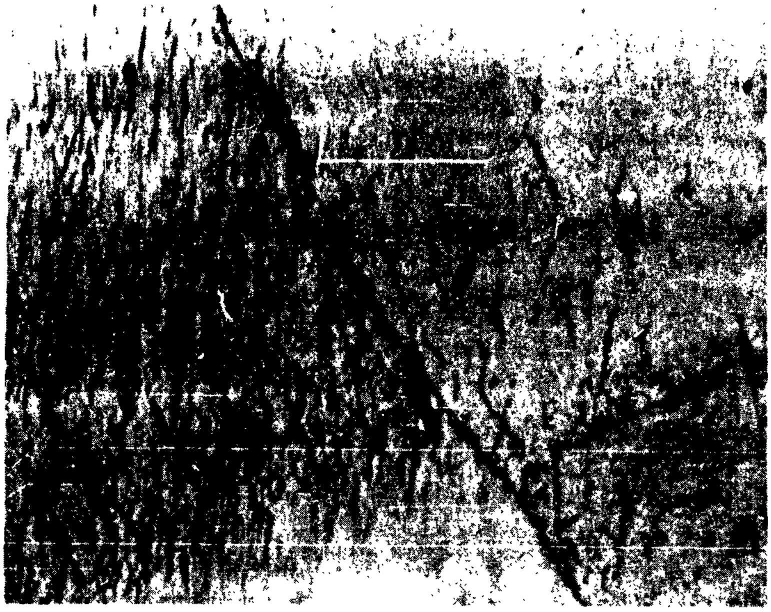


Figure 23 - Photomicrograph of banded area in forged TZM arc melted material. 1000X mag. Etched with modified Murakami's Reagent.

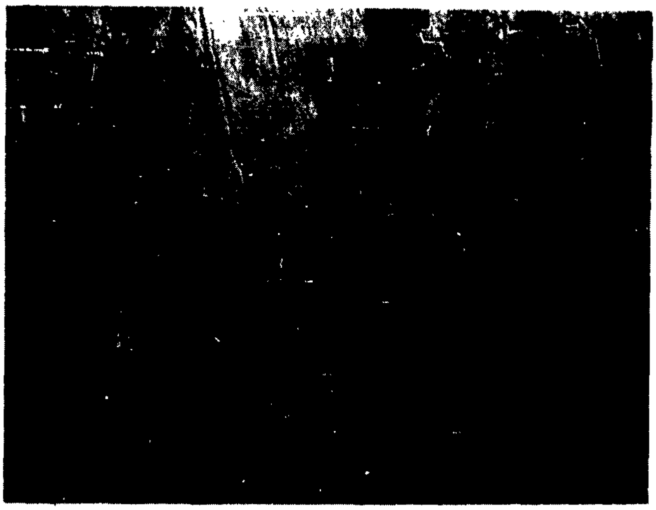


Figure 24 - As-forged, Group I, arc melted TZM forging. 100X mag. Etched with modified Murakami's Reagent.

Figure 25 - As-forged, Group I, arc melted TZM forging heated at 2350°F for two hours subsequent to forging. 100X mag. Etched with modified Murakami's Reagent.

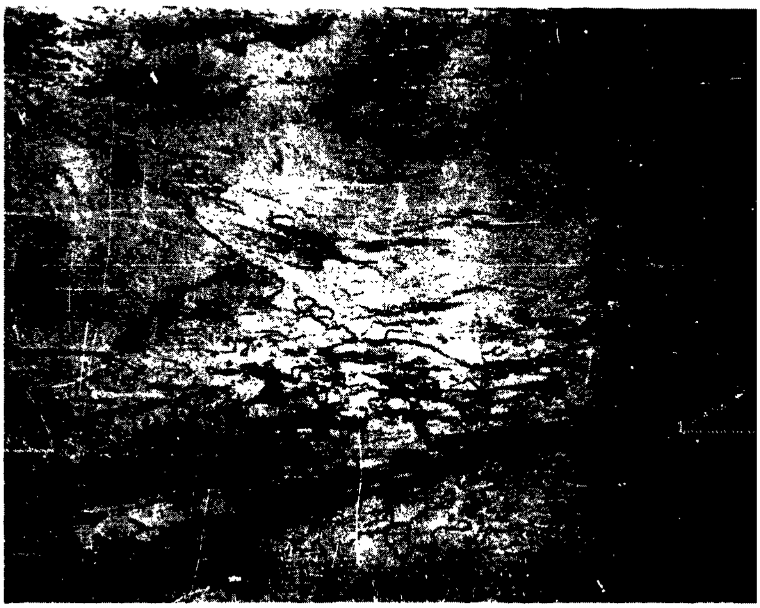


Figure 26 - As-forged, Group I, arc melted TZM forging heated at 2350°F for three hours. Small amount of recrystallization observed primarily along grain boundaries. 100X mag. Etched with modified Murakami's Reagent.

Figure 27 - Pressed and sintered TZM billet forged in Group III. Heated to 2500°F for one hour. Very small grains detected along grain boundaries. 1000X mag. Etched with modified Murakami's Reagent.

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